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Compact Cr:ZnS channel waveguide laser operating at 2333 nm

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Abstract: A compact mid-infrared channel waveguide laser is demonstrated in Cr:ZnS with a view to power scaling chromium laser technology utilizing the thermo-mechanical advantages of Cr:ZnS over alternative transition metal doped II-VI semiconductor laser materials. The laser provided a maximum power of 101 mW of CW output at 2333 nm limited only by the available pump power. A maximum slope efficiency of 20% was demonstrated.

OCIS codes: (160.6990) Transition-metal-doped materials; (230.7380) Waveguides, channeled; (220.4610) Optical fabrication; (140.5680) Rare earth and transition metal solid-state lasers.

References and links

1. L. D. DeLoach, R. H. Page, G. D. Wilke, S. A. Payne, and W. F. Krupke, "Transition metal-doped zinc chalcogenides: spectroscopy and laser demonstration of a new class of gain media," IEEE J. Quantum Electron. **32**(6), 885–895 (1996).
2. J. McKay, K. L. Schepler, and G. C. Catella, "Efficient grating-tuned mid-infrared Cr^{2+}:CdSe laser," Opt. Lett. **24**(22), 1575–1577 (1999).
3. M. Mond, D. Albrecht, E. Heumann, G. Huber, S. Kück, V. I. Levchenko, V. N. Yakimovich, V. G. Shcherbitsky, V. E. Kisel, N. V. Kuleshov, M. Rattunde, J. Schmitz, R. Kiefer, and J. Wagner, "1.9- m and 2.0-m laser diode pumping of Cr^{2+} :ZnSe and Cr^{2+} :CdMnTe," Opt. Lett. **27**(12), 1034–1036 (2002).
4. R. H. Page, K. I. Schaffers, L. D. DeLoach, G. D. Wilke, F. D. Patel, J. B. Tassano, Jr., S. A. Payne, W. F. Krupke, K. T. Chen, and A. Burger, "Cr^{2+}-doped zinc chalcogenides as efficient, widely tunable mid-infrared lasers," IEEE J. Quantum Electron. **33**(4), 609–619 (1997).
5. U. Hömmerich, X. Wu, V. R. Davis, S. B. Trivedi, K. Grasza, R. J. Chen, and S. Kutcher, "Demonstration of room-temperature laser action at 2.5 mum from Cr^{2+}:$Cd_{0.85}Mn_{0.15}Te$," Opt. Lett. **22**(15), 1180–1182 (1997).
6. P. A. Berry and K. L. Schepler, "High-power, widely-tunable Cr^{2+}:ZnSe master oscillator power amplifier systems," Opt. Express **18**(14), 15062–15072 (2010).
7. T. J. Carrig, G. J. Wagner, W. J. Alford, and A. Zakel, "Chromium-doped chalcogenide lasers," *Lasers and Electro-Optics Society, 2005. LEOS 2005. The 18th Annual Meeting of the IEEE*, Oct. 2005, **5460** (2004).
8. E. Sorokin, I. T. Sorokina, M. S. Mirov, V. V. Fedorov, I. S. Moskalev, and S. B. Mirov, "Ultrabroad continuous-wave tuning of ceramic Cr:ZnSe and Cr:ZnS lasers," in *Advanced Solid-State Photonics*, (Optical Society of America, 2010), AMC2.
9. I. S. Moskalev, V. V. Fedorov, and S. B. Mirov, "Tunable, single-frequency, and multi-watt continuous-wave Cr^{2+}:ZnSe lasers," Opt. Express **16**(6), 4145–4153 (2008).
10. K. L. Schepler, R. D. Peterson, P. A. Berry, and J. B. McKay, "Thermal effects in Cr^{2+}:ZnSe thin disk lasers," IEEE J. Sel. Top. Quantum Electron. **11**(3), 713–720 (2005).
11. I. T. Sorokina, "Cr^{2+}-doped II–VI materials for lasers and nonlinear optics," Opt. Mater. **26**(4), 395–412 (2004).
12. H. Baker, J. Lee, and D. Hall, "Self-imaging and high-beam-quality operation in multi-mode planar waveguide optical amplifiers," Opt. Express **10**(6), 297–302 (2002).
13. J. Nilsson and D. N. Payne, "Physics. High-power fiber lasers," Science **332**(6032), 921–922 (2011).
14. P. A. Berry, J. R. Macdonald, S. J. Beecher, S. A. McDaniel, K. L. Schepler, and A. K. Kar, "Fabrication and power scaling of a 1.7 W Cr:ZnSe waveguide laser," Opt. Mater. Express **3**(9), 1250–1258 (2013).
15. S. B. Mirov, V. V. Fedorov, I. S. Moskalev, and D. V. Martyshkin, "Recent progress in transition-metal-doped II-VI mid-IR lasers," IEEE J. Sel. Top. Quantum Electron. **13**(3), 810–822 (2007).
16. I. T. Sorokina and K. L. Vodopyanov, *Solid-State Mid-Infrared Laser Sources* (Springer, 2003).

17. S. B. Mirov, V. V. Fedorov, I. Moskalev, S. Vasyliev, D. Martyshkin, M. Mirov, and V. P. Gapontsev, “Recent Advances in High Power, High Energy Tunable Cr:ZnS/Se Lasers,” in *CLEO: 2013*, (Optical Society of America, 2013), CTu3D.1.
18. R. R. Gattass and E. Mazur, “Femtosecond laser micromachining in transparent materials,” Nat. Photonics **2**(4), 219–225 (2008).
19. Y. Nasu, M. Kohtoku, and Y. Hibino, “Low-loss waveguides written with a femtosecond laser for flexible interconnection in a planar light-wave circuit,” Opt. Lett. **30**(7), 723–725 (2005).
20. J. O. Ndap, K. Chattopadhyay, O. O. Adetunji, D. E. Zelmon, and A. Burger, “Thermal diffusion of Cr^{2+} in bulk ZnSe,” J. Cryst. Growth **240**(1-2), 176–184 (2002).
21. U. Demirbas, A. Sennaroglu, and M. Somer, “Synthesis and characterization of diffusion-doped Cr^{2+}:ZnSe and Fe^{2+},” ZnSe **28**, 231–240 (2006).
22. S. B. Mirov and V. V. Federov, “Mid-IR microchip laser: ZnS:Cr2+ laser with saturable absorber material,” (US Patent No 6,960,486., 2009).
23. A. Okhrimchuk, V. Mezentsev, A. Shestakov, and I. Bennion, “Low loss depressed cladding waveguide inscribed in YAG:Nd single crystal by femtosecond laser pulses,” Opt. Express **20**(4), 3832–3843 (2012).
24. J. R. Macdonald, S. J. Beecher, P. A. Berry, G. Brown, K. L. Schepler, and A. K. Kar, “Efficient mid-infrared Cr:ZnSe channel waveguide laser operating at 2486 nm,” Opt. Lett. **38**(13), 2194–2196 (2013).

1. Introduction

The mid-infrared atmospheric transmission window at 2-5 μm contains many fundamental and overtone molecular vibrational absorption lines. As such, laser sources in this wavelength range are required for a host of applications including laser radar (LIDAR), atmospheric sensing, and laser surgery. In 1996 Deloach et *al.* [1], characterized many transition metal doped II-VI semiconductor gain media identifying multiple materials suitable for mid-infrared laser emission. Materials such as Cr:ZnSe, Cr:CdSe, Cr:Cd_xMn_{1-x}Te and Cr:ZnS were shown to possess many desirable characteristics such as large emission cross-sections, broad gain and absorption bandwidths, no excited state absorption and room temperature operation, with all of these materials having since demonstrated mid-infrared laser operation [2–5]. Chromium laser technology has matured to demonstrate high power, widely tunable, and narrow line-width operation at room temperature. Specifically, Cr:ZnSe has exhibited high power continuous wave (CW) and pulsed outputs of 14.5 W and 18.5 W respectively [6, 7], wide tunability from 1973 to 3349 nm [8], and single longitudinal mode output [9]. However, even with careful consideration of heat removal, pump source, system geometry and configuration, e.g. MOPA systems, the power scaling of Cr:ZnSe sources has been limited by the high thermo-optic coefficient, $\left(\frac{\partial n}{\partial T}\right)$, of the gain media [10, 11]. An elegant solution to further power scaling and system size reduction would be to employ waveguide geometry in order to mitigate the effects of thermal lensing in the gain medium [12, 13]. This approach has been used successfully to demonstrate Watt-class laser output in Cr:ZnSe waveguides [14]. Cr:ZnS offers a significant improvement of these thermo-mechanical properties over that of Cr:ZnSe. Both a lower thermo-optic coefficient of 46×10^{-6} K^{-1} compared to $70 \times 10^{-6} K^{-1}$ of Cr:ZnSe [11], and higher thermal conductivity [15]. The increase in thermal conductivity, from 18 to 27 $W{\cdot}m^{-1}K^{-1}$, for Cr:ZnSe and Cr:ZnS respectively [16], places Cr:ZnS as an interesting material for power scaling applications. Indeed, in standard bulk laser cavities, these systems have been shown to be capable of 21.5 W CW operation [17]. As such Cr:ZnS waveguide lasers are an attractive prospect for both power scaling of chromium laser technology and the realization of compact mid-infrared sources with the vibration insensitive robustness of waveguide sources.

2. Waveguide fabrication

The fabrication of the channel waveguide structures was performed by ultrafast laser inscription (ULI). ULI relies on the nonlinear absorption of tightly focused ultrashort pulses below the surface of a transparent dielectric. The high irradiances generated at the focus of the inscription beam allows nonlinear processes such as multi-photon, tunneling and

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avalanche ionization which in turn allow a transfer of energy to the material lattice [18]. This energy transfer may result in a localized refractive index change to the material which can be exploited for the fabrication of waveguide structures. Through careful control of the inscription parameters, waveguides of arbitrary cross-section can be created by translating the target substrate through the focus [19].

Waveguides were fabricated in a 6 × 5 × 2 mm polycrystalline Cr:ZnS sample with Cr ion concentration of 8.3 × 10^{18} cm^{-3} achieved by post-growth thermal diffusion. Conventional post-growth thermal diffusion technique utilizes thermally activated diffusion of transition metal ions into the II-VI hosts and features a qualitative nature of doping (hard to fabricate crystals with a pre-assigned concentration of dopant), non-uniform doping, large concentration gradients, degradation of optical quality of the crystals due to sublimation of Zn and Se sub-lattices, and poor repeatability [20, 21]. Mirov et *al*. [15, 22] have developed and commercialized a new quantitative thermo-diffusion technology enabling fabrication of gain and passive materials with pre-assigned concentration of optical centers, fast and uniform doping through crystals of relatively large, up to 6 mm, thickness, suppressing sublimation processing during annealing, and preserving high optical quality of starting material - optical losses of the Cr doped crystals with concentration 10^{19} cm^{-3} are below 1-3% per pass. Cr:ZnS prepared by this technology has been used in this work.

The waveguide design was an annular cross-section depressed cladding structure fabricated from an arrangement of individual modification elements similar to the design previously demonstrated in Nd: YAG [23] and Cr:ZnSe [24]. A schematic diagram of the waveguide cross-section is displayed in Fig. 1(a). The inscription laser (IMRA µJewel D400) supplied 400 fs pulses at a repetition rate of 100 kHz with a range of pulse energies investigated from 0.3 to 1.5 µJ. The beam was linearly polarized, perpendicular to the waveguide propagation axis, and was focused beneath the sample surface with a 0.6 NA aspheric lens. Waveguide structures of 30-80 µm diameters were fabricated from 40 and 80 individual modification elements. Sample translation velocities of 9-20 mm·s^{-1} were also investigated as a key parameter. Following the inscription process the sample was ground and polished to remove any damage and waveguide structure non-uniformity at the sample edges. Significant differences in the resultant structures were observed between Cr:ZnS and those previously reported in Cr:ZnSe. In Cr:ZnSe, waveguides with cross-sectional diameters of 80 µm were found not to support guiding at the signal or pump wavelength but diameters as small as 50 µm were found to be successful in Cr:ZnS. An example of this can be seen in Fig. 1(b) where the cross-section of a 60 µm waveguide retains an unmodified core region. Reducing the waveguide cross-section will allow an increase in mode confinement and consequently higher irradiances for a given average power propagating through the waveguide.

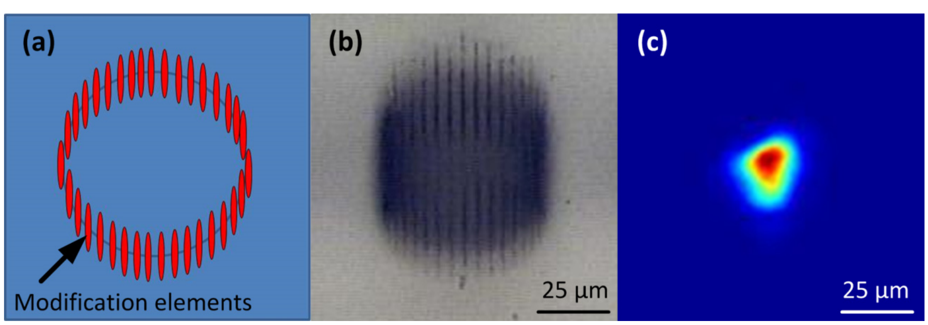

Fig. 1. (a) Schematic diagram of annular depressed cladding waveguide structure in Cr:ZnS. (b) optical micrograph of 60 µm diameter waveguide end facet composed of 40 modification elements. (c) associated laser output mode at 2.33 µm imaged at waveguide end facet. Image taken using the 60%R output coupler cavity.

3. Waveguide laser operation

The Cr:ZnS channel waveguides were built into a compact cavity, 6 mm in length, by butt-coupling a dichroic mirror and output coupler to opposite end facets of the crystal. The pump laser for the system was a 1928 nm Tm:Fiber laser (AdValue) which provided 1.5 W CW output. This was coupled into the waveguide cavity using an AR coated 50 mm focal length CaF_2 plano-convex lens. The input dichroic mirror was AR coated for the pump wavelength and 99.6% reflective for 2050 – 2430 nm. A range of output couplers was investigated with 60, 70 and 80% reflectivity for 1700-2700 nm and so spanning the center of the material emission bandwidth at approximately 2350 nm [1]. As the Cr:ZnS crystal was uncoated the calculated Fresnel reflections were subtracted from the incident pump power to provide a value for the pump power provided to the waveguide. This corresponds to a maximum available pump power of 1.2 W that may be coupled into the waveguide. Coupling losses and unabsorbed pump were not accounted for providing a lower bound to the measured efficiency of the waveguide laser. The best performance was obtained for a waveguide of 60 μm diameter constructed from 40 individual modification elements and inscribed at a translation velocity of 20 $mm{\cdot}s^{-1}$. The spectrum of the laser output was measured using a 300 mm monochromator (Gilden Photonics) capable of resolving a minimum line-width of 0.4 nm. The spectrum was observed to be centered on 2332.6 nm with a FWHM of 2.2 nm. The laser spectrum and performance can be seen in Fig. 2 and Fig. 3 respectively below.

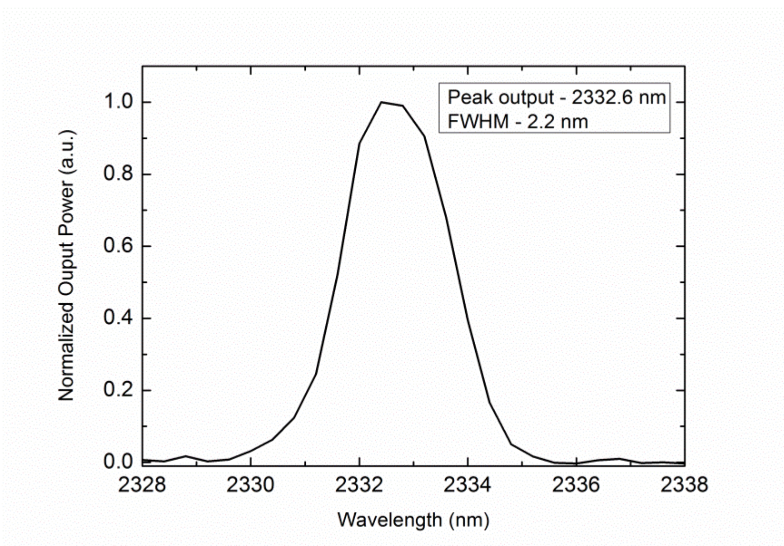

Fig. 2. Normalized spectrum of Cr:ZnS waveguide laser measured using a 300 mm monochromator. The laser emission peak was observed at 2332.6 nm and a FWHM of 2.2 nm was measured for the output using a 60% reflective output coupler.

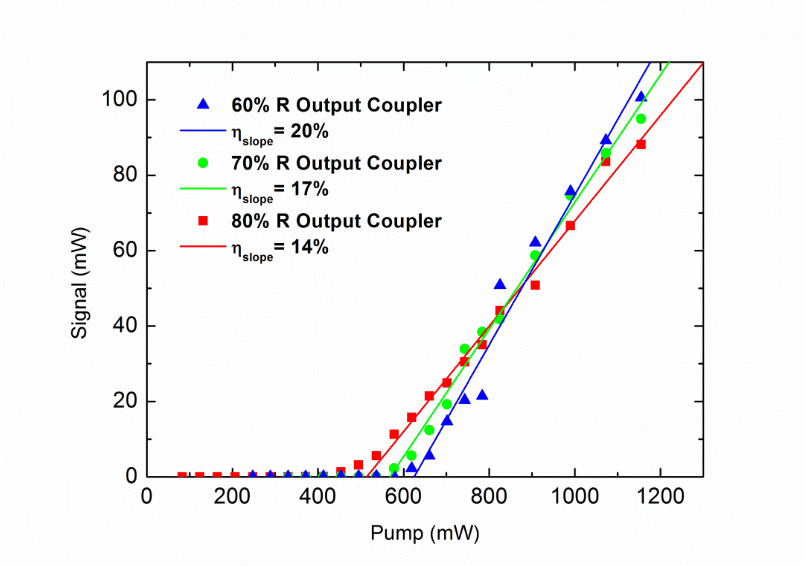

Fig. 3. Laser performance of the Cr:ZnS waveguide laser at 2332.6 nm. A maximum output power of 101 mW with a slope efficiency of 20% is demonstrated using a 60%R output coupler.

A maximum output power of 101 mW was achieved using the 60% reflectivity output coupler. The laser threshold occurred at an input power of 615 mW and a slope of efficiency of 20% was recorded. Lower thresholds of 570 mW and 450 mW were measured for the 70% and 80% reflectivity output couplers, with slope efficiencies of 17% and 14% respectively. The spatial profile of the laser light emerging from the waveguide end facet was imaged onto a mid-infrared camera (FLIR SC7000), this is shown alongside the waveguide end facet in Fig. 1(b) and 1(c). The observed profile was near 2-D Gaussian with slight asymmetry in both axes. Importantly, no thermally induced 'roll over' of the laser output was observed up to the maximum pump measurement of 1155 mW coupled into the waveguide. This renders the waveguide structures suitable for testing with high power operation as described with Cr:ZnSe by Berry et *al.* [14]. The efficiency of the laser is expected to be limited by the propagation losses of the waveguide structures and the absorption efficiency of Cr:ZnS at 1928 nm. Full characterization and optimization of the waveguides to reduce intra-cavity losses will allow for improved laser performance, with higher efficiencies and lower lasing thresholds. In addition to this, AR coating of the waveguide end facets and selection of a pump source closer to the peak of the absorption cross-section (approximately 1680 nm [11]) are also expected to improve device efficiency. An alternative pump source such as an Er: fiber laser operating at 1550 nm would be subject to approximately double the absorption cross-section and negligible emission cross-section compared to the 1928 nm Tm: fiber pump [16]. However, for high power operation, the increased quantum defect when utilizing a shorter wavelength pump source may hinder performance through additional heating of the structure. Consideration of the optimum waveguide length for absorption of longer pump wavelengths will therefore be an important factor in the design of high power Cr:ZnS waveguide laser sources.

4. Summary

In summary, a Cr:ZnS channel waveguide laser has been successfully demonstrated with a compact cavity of 6 mm. A maximum output power of 101 mW was achieved for 1155 mW of 1928 nm pump with a slope efficiency of 20% at 2332.6 nm and a 2.2 nm FWHM line-width. A substantial increase in laser performance is expected with further optimization of the waveguide structures to reduce signal propagation losses. The preferable thermo-mechanical properties of Cr:ZnS against other Cr doped II-VI semiconductor laser materials paves the way for investigations into power scaling of Cr laser technology as well as the development of compact, mid-infrared fixed wavelength and tunable sources.

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